Bimanual interference associated with the selection of movement targets

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Abstract

Three experiments were conducted to identify the locus of bimanual interference observed during the production of reaching movements. The movements had either the same or different amplitude and were directed towards identically or differently colored target circles. In Experiment 1, reaction times for movements of different amplitudes to targets of the same color were faster than for movements of the same amplitude to targets of different colors. This indicates that the cost to initiate responses of unequal amplitudes arises during selection of the target of the movement rather than during motor programming. Experiments 2 and 3 further specify the sources of interference found in target selection. Reaction time costs are found with unimanual responses when the target is presented among distractors associated with responses for the other hand. This indicates that the costs may arise through an assignment problem of response-rules to the respective hands.

Bimanual interference associated with the selection of movement targets

We typically use our two hands in a coordinated fashion to achieve a common goal. When unscrewing a bottle or tying a knot, the actions of the two hands have to be finely tuned in relation to each other. Constraints on bimanual performance become apparent when we use our hands to achieve different goals at the same time. Consider for example the task of picking out good cherries among rotten ones from a tray in the supermarket, with either one or two hands. If our hands could work perfectly independently, we should be able to pick out twice as many cherries with both hands than with only one. This, however, is not the case. This limitation may be due to our inability to plan or execute independent movements with the two hands at the same time. Alternatively, we may have problems in selecting in parallel the goals of the two reaching movements based on a number of criteria as size, color, smoothness, etc. for the two hands. The focus of the present article is to determine the processing stage that gives rise to the performance limitations during bimanual movements.

In the laboratory, these limitations of bimanual performance have been studied with tasks that require the simultaneous production of two movements with either symmetric or differing spatial characteristics. Compared to when the movements are the same for the two hands, producing different movements with the two hands prolongs initiation times (Franz, Eliassen, Ivry, & Gazzaniga, 1996; Spijkers, Heuer, Kleinsorge, & van der Loo, 1997) and significant distortions of the spatial trajectories can be observed (Franz, Zelaznik, & McCabe, 1991; Kelso, Putnam, & Goodman, 1983; Sherwood, 1990; Spijkers & Heuer, 1995).

Spijkers and his associates have explored the question of when limitations arise in a series of papers (1997; Spijkers, Heuer, Steglich, & Kleinsorge, 2000). In one study, participants were required to execute fast lateral movements (outward and back) with their arms. The target amplitude of each movement was cued by the presentation of two bars, one on the left and one on the right of a computer monitor. Each bar could either be short or long. Reaction times were nearly 100 ms longer when the two movements were incongruent (i.e., one short and the other long) compared to when the two movements were congruent (i.e., both short or both long). The authors proposed that this increase reflected interference at the stage of motor programming (see Rosenbaum, 1980; Rosenbaum & Kornblum, 1982). Programming was fast when the only unknown parameter, movement amplitude, was set to the same value for each hand. When different parameters needed to be specified, cross talk was hypothesized to occur between the programming process required for the right arm and that required for the left arm. This cross talk presumably led to the increase in RT on incongruent trials.

A challenge to the programming interpretation comes from a recent study in which the target locations were specified directly (Diedrichsen, Hazeltine, Kennerley, & Ivry, in press). That is, visual signals were presented on the table surface and the participants were instructed to move as quickly as possible to the target locations. Under these conditions, no differences were found in RT between congruent and incongruent movements, regardless of whether incongruency was defined as a difference in movement amplitude or direction. Indeed, the RT on bimanual trials with direct cues was as fast as on unimanual trials. Assuming that motor programming and execution processes are similar for direct and symbolically cued movements, these results indicate that the interference observed in earlier studies is unlikely to be attributed to either of these stages. Rather, the interference visible in the RT data is likely due to a processing stage associated with identification of the stimulus and/or selection of the appropriate response.

Although rarely discussed as such, bimanual reaching studies constitute a form of a dual-task paradigm. Limitations in dual task performance have been one of the central topics in cognitive psychology and have played a critical role in the development of analytic tools for specifying processing stages across a range of tasks (Pashler, 1998b). One example is the literature on the psychological refractory period (McCann & Johnston, 1992; Pashler, 1994; Telford, 1931). In these studies, participants have to respond to two stimuli in rapid succession. When the stimulus onset asynchrony (SOA) between the tasks is short, the RT for the second task is delayed. This limitation has been attributed to a response-selection bottleneck (but see Meyer & Kieras, 1997; Pashler, 1984, 1998a). By this view, it is assumed that stimulus identification and response execution for the two tasks can occur in parallel; the limitation is hypothesized to arise due to overlapping demands of the two tasks on a common response selection process.

Response selection for one task must be completed before this operation can be performed for the other task. With short SOAs, this delay will be manifest as an increase in RT for the second task.

Spijkers et al. (2000) used a PRP paradigm with bimanual reversal movements of same or different amplitudes. They found that at short SOA the initiation of the second movement was considerably delayed, when the movement amplitudes were incongruent. They interpreted their results as interference of temporally overlapping motor programming processes. With their symbolic bar stimuli as cues, however, the cost on incongruent trials might be associated with the demands associated with processing non-identical cues or because non-identical "abstract" movement codes had to be selected. The first hypothesis was ruled out by a control condition in which the first stimulus had to be identified, but no response was required. The participants showed similar RTs in this condition on congruent and incongruent trials. The second possibility was considered by the authors, but dismissed because "the distinction between response selection and amplitude specification is inappropriate for our experimental paradigm […]. As argued by Rosenbaum (1983), selection of a movement is equivalent to specifying its parameters" (Spijkers et al., 2000, p. 1103).

This argument may be valid in cases in which the movements are not directed to specific targets but are instead determined by symbolic stimuli that specify the movement in terms of kinematic parameters. Under these symbolic conditions, movements may be mentally represented in terms of these task-defined movement parameters. That is, when participants are told to make a long or short movement in response to the letter "L" or "S", then they likely represent possible action as either a "long movement" or "short movement". Selection of the response then operates on codes in terms of movement parameters. Bimanual interference arises when two actions with different representations have to be selected. However, when the movement is directed towards an object, the response code may encompass characteristics of the goal object rather than the movement parameters. For example, imagine you want retrieve a tool from a cluttered tool drawer. Deciding which object you want to pick out would constitute a response-selection process. The location of that object and its orientation would then dictate the motor programming requirements, a process that would follow selection. In this way, the selection of the movement goal and the specification of the movement parameters to get to the goal can be separated.

This distinction suggests two possible loci for bimanual interference. If cross talk arises during the selection of responses, then the pattern of interference should depend heavily on how the possible actions are represented. If cross talk arises during the specification of motor parameters, then the interference should be determined by the kinematic properties of the movements. In Experiment 1 participants were instructed to select an object for each hand and then directly reach for it. The reaches could require movements of the same or different amplitudes. The goal of this study was to examine whether the interference should be attributed to early stages (stimulus identification and response selection) as has been hypothesized in PRP studies and our earlier direct reaching study (Diedrichsen et al., in press) or late stages (motor programming and motor execution) as has been assumed in most bimanual reaching studies.

Experiment 1

The experiment was conducted in an apparatus which allowed participants to reach directly for visually presented targets (Figure 1). Four target locations were defined on each trial by the presentation of four colored circles that formed the corners of an invisible rectangle (see Figure 2). The participants' task was to execute bimanual reaching movements, with the left hand moving to one of the two left-side targets and the right hand moving to one of the two right-side targets. The target locations were specified by the presentation of two small, colored circles (cues) near the center of the display. The color of each of these cues matched the color of one of the two target circles on the corresponding side, thus indicating the target location for that trial. The onset of the cues also served as the imperative signal. For example, if the colors of the cues on the left and right were blue and yellow, respectively, then the participant would reach to the blue target location on the left and the yellow target location on the right.

Please insert Figure 1 here

Please insert Figure 2 here

There were three conditions. In the <u>four-color condition,</u> unique colors were used for the four target locations. In the other two conditions, only two colors were used with each color appearing at one of the two target locations on each side. In the <u>two-color uncrossed</u> condition, one color was used for both far target locations and the second color was used for both near target locations. In the <u>two-color crossed</u> condition, one color was used for the target locations along one diagonal and the other color was used for the target locations along the other diagonal.

The experiment was designed to determine the locus of interference when planning bimanual movements of unequal amplitude. Consider first the four-color condition. The target colors for the two hands were always different in this condition. If interference reflects competition at the stage of stimulus identification or response selection, we should expect similar performance for all of the movement combinations. This is because on every trial two different cues must be identified and targets of different colors must be selected. However, if interference arises at the stage of motor programming, then we should observe a movement congruency effect. That is, when participants have to execute movements of the same amplitude (either short-short or long-long) movement initiation should be faster than when the movements have different amplitudes (short-long or long-short).

Next consider the two-color conditions. For these conditions, the two target colors were the same on half of the trials and different on half of the trials. In the uncrossed condition, identical target colors indicate movements of the same amplitude (both short or both long). Thus, independent of the locus of interference, congruent movements should be initiated faster than incongruent movements for this condition, because the former involves identifying the same color, selecting targets of the same color, and programming movements of identical amplitudes. In contrast, early and late models of interference make opposite predictions for the crossed condition. When the cues and colors of the target locations are identical, stimulus identification and response selection should be facilitated since only one color needs to be evaluated. Programming should be difficult, however, because the required movements are of unequal amplitude.

The reverse holds for the situation in which the target colors are different, thus requiring movements of equal amplitude. Now stimulus identification and response selection should be difficult, but programming would be easy.

To summarize, the comparison of same and different target color trials in the two-color conditions provides a strong comparison of models that attribute bimanual interference to early stages (stimulus identification/response selection) and late stages (response programming or execution). The early-stage model would be favored if performance was fastest when the cues and colors of the target locations were identical regardless of whether these targets involved movements of equal or unequal amplitude. The late-stage model would be favored if performance was fastest when the movements were of identical amplitude regardless of whether or not the targets were specified by the same or different colors. It is, of course, possible that interference can arise at all stages. If so, we would expect to find performance influenced by both target color correspondence (same or different target colors) and target amplitude (same or different movement amplitudes).

Method

Participants. Ten participants were recruited from the University of California, Berkeley community. All were right-handed and ranged in age from 18 to 28 years.

Apparatus and Stimuli. A mirror-reflecting system was used for the presentation of all stimuli (Figure 1). This system consisted of a computer projector (Plus UP 800) and three parallel surfaces (each 100 x 77 cm): a table surface along which movements were made; a projection surface onto which the stimuli were presented; and a mirror surface which reflects the stimuli onto the table surface. The table surface was at a height of 75 cm. The projection surface was 48 cm above the table and the mirror was placed halfway between the projection and table surfaces. The projector was 112 cm above the projection surface. The subject viewed the apparatus from the side, looking onto the mirror, the head constraint by a chin rest. With this arrangement, the stimuli presented onto the projection surface appear to lie on the table. The phenomenal experience of the participants is that they are reaching directly to the target locations, although their hands are blocked from view by the mirror. Head position was restrained by the use of a chin rest.

A 3-d movement recording system (Ascentech mini-bird system) was used to monitor the positions of the two hands. Small antennas (15 x 8 x 8 mm) were taped to the tip of each index finger. These antennas respond to magnetic signals generated by a transmitter and provide an output signal of current position (x,y,z coordinates). The sampling rate was 140 Hz.

Filled colored circles were used to indicate the four target locations. Each circle was 3.6 cm in diameter and they were displayed at the vertices of an imaginary rectangle. The width of the rectangle was 15.4 cm and the length was 10 cm. The cues were presented near the center of the rectangle. Each was a circle, 1.2 cm in diameter, with a distance of 3.8 cm between the two cues. In addition, two unfilled, white circles were displayed at the start of each trial to indicate the starting position for each index finger. These circles were 3.6 cm in diameter and were 10 cm from the center of the nearest target locations. Thus, the movements for each hand could be either 10 cm or 20 cm. As noted above, the mirror screen prevented the participants from seeing their hands. However, the position of the index fingers was continuously monitored and displayed as a small dot (2-mm diameter) on the table surface. The participants' impression was that they were moving in the dark with only the tips of their fingers visible as they moved to the colored target locations.

Procedure. Each trial began with the illumination of the two starting circles. The left and right index fingers were then moved into these circles. After the starting position had been maintained for 1 s, the four target locations were presented.

In the four-color condition, the clearly distinguishable colors green, red, blue, and yellow were randomly assigned to the circles at these four locations. In the two-color conditions, two of these colors were randomly selected and assigned to the circles at the four locations in an uncrossed or crossed fashion. Every color combination was presented an equal number of times over the course of the experiment. After a variable time delay of 1-2 s the two cues appeared at the center of the imaginary rectangle. Participants were instructed to move their fingers as fast as possible to the circle that matched the color of the cue on the corresponding side. For example, if the left cue was blue, then the participant should move his or her left index to the target location on the left that is blue. They were instructed, to initiate the movements of the two hands simultaneously. The trial ended when the velocity for both fingers stayed below 5 cm/s for a continuous 80 ms epoch. At this time, all stimuli were turned off and an inter-trial interval of 500 ms started, before the starting circles were presented again.

The experiment began with a practice block of 36 trials. Following this each participant completed 8 blocks of 36 trials each. There were 12 different trial types created by the factorial combination of three experimental conditions (four-colors, two-colors crossed and two-colors uncrossed) and four movement combinations (short-short, long-long, short-long and long-short). Each combination occurred three times within a test block. The trial types were randomly ordered within a block and, across blocks, all possible color combinations were counterbalanced for each trial type. After each block the participants received feedback indicating mean reaction time, mean movement time, and the percentage of trials in which the movement terminated inside the target location.

Data analysis. For the purpose of data analysis, reaction times and movement times were calculated offline with a lower threshold than the on-line calculations for immediate feedback. The recorded trajectory for every hand was smoothed by a Gaussian kernel of the width 14 ms. Then the velocity and acceleration profile was calculated and the acceleration function was further smoothed by a 25 ms-wide Gaussian kernel. The RT for each hand was defined as the point when the tangential velocity of the receiver exceeded 2 cm/s for the first time and stayed above this velocity for at least 100 ms. The end of the movement was defined as the point at which the velocity dropped below this same threshold, and MT was calculated as the difference between this point and the movement onset. The acceleration function of each hand was used to determine possible subcomponents of the movements. A subcomponent was defined as a phase in which acceleration reached at least 100 cm/s^2 for 20 ms followed by a subsequent deceleration phase.

Results and Discussion

Trials were excluded from the analyses if: (a) the recording was terminated before the velocity had dropped below threshold (4%), (b) the movements were not performed simultaneously, operationalized as a difference in movement onset time for the two hands greater than 150 ms (5.8 %), or (c) one of the hands terminated the movement near the incorrect target (2%).

Please insert Figure 3 here

The mean reaction times are shown in Figure 3, with separate bars shown for responses in which the movement amplitudes were the same (congruent) or different (incongruent). In the uncrossed condition RTs on congruent trials were 185 ms faster than on incongruent trials, $t(9) = 5.39$, $p < .001$. Strikingly, this effect is completely reversed in the crossed condition. For this condition, RTs on incongruent trials are 185 ms faster than on congruent trials. Note, though, that the color of the cues and target locations is identical on incongruent trials in the crossed condition. Thus, the results fail to support the hypothesis that interference on bimanual reaching tasks is due to conflicts that arise at the motor programming stage. Rather, they indicate that, in the current design, interference arises at earlier processing stages such as those associated with stimulus identification and/or response selection. The results in the four-color condition provide further support for these claims. First, no effect of congruency was found here, $t(9) = .38$, $p = .71$. Second, the RTs in the four-color condition were comparable to that observed in the two-color conditions in which the two cues had different colors. On all trials in the four-color condition, target selection required the analysis of two different colors.

As noted above, RTs were fastest when the color cues were identical and targets of identical color had to be selected. We can ask whether there is an additional effect of congruency. When the two colors were the same, trials requiring movements of the same amplitude (uncrossed condition) were 33 ms faster than trials requiring movements of different amplitude (crossed condition), $t(9) = 4.01$, $p = .003$, suggesting that there was a congruency effect. However, when the two colors were different in the two-color conditions, a 32 ms advantage was again found for the uncrossed condition compared to the crossed condition, $t(9) = 2.85$, $p = .019$ even though the movements in the former condition were now incongruent. This suggests that there was an overall cost associated with the crossed condition. The data do not provide any evidence of a congruency effect related to programming movements of either the same or different amplitude.

Please insert Figure 4 here

The movement time results are presented in Figure 4. An assimilation effect was observed in the four-color condition: when a short movement was paired with a long movement, MT increased compared to when both movements were short, t(9) = 4.00, p=.003; when a long movement was paired with a short movement, MT decreased compared to when both movements were long, however not significantly, t(9) = 1.77, p = .11. This effect represents the tendency of the participants to synchronize both the onset and offset of the two movements (Kelso, Southard, & Goodman, 1979; Kelso et al., 1983). However, the synchronization between the hands in case of movements of different amplitudes was not perfect. When a short and a long movement were paired, the short movement was still 71 ms faster than the long movement, t(9) = 6.09, p<.001. (see also Marteniuk, MacKenzie, & Baba, 1984).

A different pattern was found in the two-color conditions. There was a main effect of condition, with the crossed condition being significantly slower than the other two, F(2,9) = 9.87, p = .001. More importantly, there was a significant 2-way interaction of condition and congruency, F(2,18) = 30.56, p < .001. In the uncrossed condition, congruent movements were executed faster than incongruent movements. The reverse was observed in the crossed condition: incongruent movements were executed faster than congruent ones. This pattern is similar to what was seen in the RT data. It is likely that at least on some trials, the movements were initiated before the response was fully selected and prepared. The conditions that had the slowest RT also had the slowest MT. As with the RT data, no evidence was found to suggest that MTs increased for trials involving movements of unequal amplitudes.

The analysis of movement components further supports the idea that part of the selection process was occasionally delayed until after movement onset. Nearly 30% of the movements showed more than one acceleration phase, indicating that the movement consisted of multiple subcomponents. In 26.2% of all short movements, a second subcomponent began close to the near target, but also in 2.7% of the short movements a second subcomponent began close to the far target. In these latter trials, the participants made an initial mistake of moving to far target and then reversed the direction correcting their movement online. In 17 % of all long movements, the second subcomponent began close to the near target, in 7.8% close to the far (terminal) target. This analysis shows that a substantial part of the movements consisted of multiple phases, often with an initial phase to above the near target and then if necessary another component towards the far target. This finding reinforces the importance to stress fast movement times to prevent the delay of target selection or motor programming processes until the movement phase. However, it is apparent that the interference for both RT and MT arises from the congruency of the cue-colors or color of objects selected, not from the congruency of movement parameters.

As a final assessment of interference associated with motor programming and execution, we measured the coupling of the produced amplitudes for the two movements. Amplitude was determined as the y-coordinate (distance from the body) at the endpoint of each movement. The amplitude of the movement for one hand was modulated by the amplitude of the movement for the other hand, $\underline{F}(1,9) = 15.63$, $\underline{p} = .003$, and the effect interacted with movement amplitude, $\underline{F}(1,9) = 8.82$, $\underline{p} < .016$. However, the direction of this modulation was opposite what would be expected if the two amplitudes were coupled. The amplitude of a short movement was not influenced by the amplitude of the other movement. The amplitude of a long movement, however, became 3 mm longer when the other movement was short. The modulation here is to increase the difference between the two movement amplitudes, however the effect is very small. Considered together with the MT data, this lets us conclude that movements of different amplitudes could be programmed and executed simultaneously without substantial interference.

In summary, neither in the reaction time or in the spatial nor temporal characteristics of the movement, did interference based on different movement amplitudes become apparent. The interference observed in the movement time seems to be due to delayed processing of response selection.

Experiment 2

The results of Experiment 1 clearly demonstrate that the constraints associated with the planning and execution of bimanual movements need not reflect interference associated with motor programming. Rather, the limitations we observed seem to be connected to processes upstream to motor programming, e.g., processing cues of different colors and/or selecting target locations defined by these colors. It is possible that these results are restricted to the particular manner in which participants were required to determine the target locations. For each response, the participants performed a matching task. They had to move to the target location that was presented in the same color as the target stimulus. Perhaps the advantage found when the targets were the same color reflected a benefit in perceptual grouping (Wertheimer, 1923). Under this condition, the cues and target locations were all the same color and thus may have formed a single perceptual group allowing for rapid identification and selection. When the color of the cues and target locations were different, two perceptual groups would be created, one on the left and one on the right. RTs are likely to be slower when these two groups have to be processed. It remains to be seen if a congruency effect could emerge when the target locations could not be selected via a matching process.

To address this issue, we eliminated the cues in Experiment 2. Rather than specify the color of the target location on a trial-by-trial basis as in Experiment 1, each participant was given a fixed rule at the beginning of the session indicating the color of the target location for all trials. In the same-target conditions, a single color served as the goal for both hands. For example, the participant might be told to always move to the red circles and one red circle and one distractor would appear on each side on every trial. In the different-targets conditions, different colors served as the goal for each hand. For example, the participant might be told to move to the red target location with the left hand and the green target location with the right hand (see Figure 5). The appearance of the colored circles at the target locations served as the imperative signals. Compared to Experiment 1, this task more closely matches natural conditions under which individuals reach for objects that satisfy internal goals in a field of distractors.

Please insert Figure 5 here

There were two types of same-target conditions. In the same-target, no-distractor condition, only two target locations were presented, one on each side. Thus, subjects in this condition could react to the onset of a stimulus on each side. Diedrichsen et al. (in press) found no congruency effect based on movement amplitudes in RT, MT, or accuracy measures when the target locations appeared without any distractors. In fact, bimanual RTs were no different than unimanual RTs when making direct reaches to targets in the forward direction. Thus, this condition provides a baseline for performance when there is no limitation associated with bimanual movements.

In the same-target, irrelevant-distractors condition, a colored distractor circle appeared at the non-target location on each side. Given our assumption that target selection is minimal (interference-free) when only the targets are present in the same-target, no-distractor condition, an increase in RT in the same-target, irrelevant-distractors condition will provide an estimate of the time required to select two locations of the same color when these targets appear along with distractors. This comparison is reminiscent of the distinction that has been made in the visual attention literature between onset detection and pop out in visual search (Egeth & Yantis, 1997; Yantis & Jonides, 1984). Moreover, it remains to be seen if a movement congruency effect will appear in the same-target, irrelevant-distractors condition given that response selection no longer entails a matching process.

We also included a different-targets, irrelevant-distractors condition. If bimanual interference reflects, at least in part, costs associated with response selection, we would expect RTs to be increased in this condition compared to the same-target, irrelevant-distractors condition. This prediction is based on the assumption that response selection is performed in a unified manner when the target locations are defined by the same color, whereas it must be performed twice when the target locations are specified by different colors. Limitations in the identification of the color cues can, in contrast to Experiment 1, not contribute to the RT effect, because the identification of the cues was eliminated in this experiment.

The fourth condition of Experiment 2 is the different-targets, relevant-distractors condition. The color of the distractor location on each side in this condition was that of the target for the opposite side. Thus, if red and green were the target colors for the left and right hands, respectively, green and red were used as the colors of the left and right distractor locations. This condition was similar to the trials of the two-color condition in Experiment 1 in which the cue colors were different. For this condition, the participants not only had to select target locations defined by two different colors, they must also ignore a distractor color that is potentially interfering. In this manner, the two types of different-targets conditions allowed us to evaluate two potential sources of interference. First, interference associated with the increased demands of response selection when two different colors are used to specify the targets can be inferred by comparing the different-targets, irrelevant-distractors condition with the same-target, irrelevant-distractors condition. Second, interference associated with interference within the selection process can be inferred by comparing the different-targets, relevant-distractors condition with the different-targets, irrelevant-distractors condition. The two sources of interference were confounded in the two-color conditions of Experiment 1.

Method

Participants. Eight healthy undergraduate students (18-36 years) from the University of California, Berkeley participated in the experiment. They were paid $10 per session plus a performance-dependent bonus.

Procedure. The procedure was similar to Experiment 1. The main change was the elimination of the cues. Rather, the target colors were specified at the beginning of each session and remained constant for the entire session.

To initiate a trial, the participant placed his or her fingers in the starting circles and held this position for 1 s. Then, the starting circles dimmed and variable foreperiod of 1-2 s started, after which either two or four colored circles appeared. The participants were instructed to move with each hand as fast as possible to the target circle. The instructions also emphasized that the participants should move smoothly and directly to the targets, and the program was modified such that the trial was terminated as soon as the velocity along the y-axis (forward direction) dropped below 4 cm/s. This change form Experiment 1 was introduced to prevent participants from reversing direction within the movement.

The experiment was conducted in two sessions, on average a week apart. In one of the sessions, a single color was designated as the target for all movements. The session started with one practice block of 32 trials of the same-target, irrelevant-distractor condition. Following this, eight test blocks of 32 trials each were administered, alternating between the same-target, no-distractor and same-target, irrelevant-distractors conditions. In the other session the subjects were instructed to move with the left hand to targets of one color and with the right hand to targets of a different color. After one practice block of 32 trials in the different-targets, irrelevant-distractor condition, the blocks alternated between the different-targets, relevant-distractors and different-targets, irrelevant-distractors conditions. Half the subjects started with the same-target session, the other half with the different-target session.

The clearly distinguishable colors red, green, blue yellow, and gray were used. The colors chosen as target colors were counterbalanced across participants. The target color(s) used in the first session were not used in the second session. For example if blue was the target color for a first session with the same-targets conditions, then this color was excluded from the second session. Similarly, if blue and green were the targets for a first session with the different-targets condition, these colors were not used in the second session.

At the end of each block, the participants received feedback reflecting RT, MT, and accuracy. They also saw a score indicating their monetary bonus for the block. The bonus was designed to emphasize speed as long as accuracy stayed above 85% correct.

Results and Discussion

Trials in which the recording was terminated prematurely (2.7%) or when the movement onset times were more than 150 ms apart (0.5%) were excluded from the analyses. Trials were scored as errors when the movement for one or both hands ended at a point closer to the distractor circle than to the target circle (for conditions in which four target locations were presented). None of these errors occurred in the same-targets conditions. In the different-targets, irrelevant-distractors condition, this type of error occurred on 1.3% of the trials. In the different-targets, relevant-distractors condition, the error rate increased to 8.4%, with both hands ending up at the wrong target on 10% of these. The error trials were excluded from further analyses.

The RT results show the increasing difficulty of the four conditions (Figure 6). As expected, the fastest RTs were observed in the same-target, no-distractor condition, with subjects initiating their reaches on average 303 ms after the onset of the stimuli. Based on our previous findings (Diedrichsen et al., in press), we assume that response selection demands are minimal in this condition. RTs for the same-target, irrelevant-distractors condition were 20 ms slower than the direct condition. A paired comparison revealed that this difference was significant, t(7) = 2.87, p = .024. This increase provides an estimate of the cost associated with selecting two targets of the same color.

Please insert Figure 6 here

The increases in RT were more dramatic when subjects reached for different target colors. RTs for the different-targets, irrelevant-distractors conditions were 57 ms slower than the same-target, irrelevant-distractors condition, t(7) = 2.44, p = .045. These costs could reflect processes required to shift the selection rules from one hand to the other (Allport, 1994). Furthermore, there could be a cost in the different-targets conditions associated with keeping track of the color-hand assignments. That is, there might be confusion as to which rule applies to which hand. Finally, the slowest RTs were observed in the different-targets, relevant-distractors condition, in which movements were initiated 81 ms more slowly that the different-targets, irrelevant-distractors condition, t(7) = 6.42, p < .001. We will consider the possible reasons for this dramatic cost in Experiment 3.

Cue identification was eliminated in Experiment 2 because the target colors remained constant for the entire session. However, we found substantially slower RTs when two colors must be used to select the target locations. Thus, the results indicate a substantial cost associated with response selection.

In correspondence with the results of Experiment 1, RTs did not differ between trials in which the two movements were of the same amplitude compared to when they were of different amplitudes. There was no reliable effect of movement congruency, F(1,7) = .75, p = .41, nor a Condition x Congruency interaction, F(3,21) = 1.46, p = .25. Thus, the current results indicate that the lack of an interference effect at the motor programming stage is not restricted to conditions in which a matching process is used to select target locations.

To assess the stability of these results over the course of a session, we ran a secondary analysis that included block number as an additional factor. Surprisingly, the effect of Block was not significant, F(3,21) = 2.138 , p = .126, and this factor did not interact with condition type, F(9,63) = .40, p = .928.

Movement times (Figure 7) were substantially shorter in Experiment 2 compared to Experiment 1. We assume this reflects the change in instructions, criterion used to terminate trials, and bonus criteria. As in Experiment 1, short movements were completed faster than long movements, F(1,7) = 226, p < .001, and were produced more slowly when the other hand was making a long movement, F(1,7) = 19.8, p =.003. Movement times differed across conditions, F(3,21) = 6.94, p = .002, with the changes in MT paralleling those found in the RT data. There was also a significant interaction between amplitude of the movement and condition, F(3,21) = 11.34, p < .001, and a three-way interaction between movement amplitude, other movement amplitude and condition, F(3,21) = 4.88, p = .01. The slowing observed for short movements when the other hand produced a long movement was smaller in the different-targets, relevant-distractors condition compared to the other conditions.

Please insert Figure 7 here

The number of movements with multiple acceleration phases was lower than in Experiment 1. Overall, 18 % of the movements consisted of two or more subcomponents. The percentage was lowest in the same-target, no-distractor condition (12%) and highest in the different-targets, irrelevant-distractors condition (26%). The percentage was 17% in the two other conditions.

As in Experiment 1, we did observe a small interaction between the two movements in terms of the produced amplitudes. The amplitude of a short movement when paired with a long one was 1 mm longer than when both movements were short. In contrast, the amplitude of a long movement when paired with a long movement was 2 mm shorter compared to when it was paired with a short movement. Again, the results are not in accord with the hypothesis of parametric coupling between movements. The participants seem to be able to successfully execute movements of different amplitudes.

In summary, Experiment 2 provides converging evidence that the difficulty in producing bimanual movements of unequal amplitude can not be attributed to motor programming or execution. Trials with movements of the same and different amplitude did not differ in RT, and the subtle differences in MT likely reflect an accommodation effect. Unlike Experiment 1, the design of Experiment 2 eliminated costs associated with cue identification. Nonetheless, we observed substantial costs when the targets were defined by two colors compared to when they were defined by one target. We have attributed this cost to response selection, hypothesizing that each color must engage the selection process. In addition, a selection hypothesis provides a parsimonious account of the results for the different-targets conditions. Although the targets were the same in both the irrelevant and relevant-distractors conditions, RTs were considerably longer in the irrelevant-distractors condition, in which the distractor color was the same as the target color for the other hand. We attribute this cost to interference within the selection process.

Experiment 3

In Experiment 3, we further examine the interference observed when the distractor color for one hand matches the target color for the other hand, that is, the increase in RT observed between the different-targets, irrelevant-distractors condition and the different-targets, relevant-distractors condition. We consider two hypotheses. First, the presence of another object of the target color could cause confusion for the selection process. For example, consider a situation in which the target color for the left hand is green. When the distractor on the right side is another color (i.e., in the irrelevant distractor), the selection process must simply identify the location of the green circle. However, when the non-target location on the right side is also green (i.e., relevant distractor), selection may be difficult here because it requires information about both color and position. Given that spatial selective attention is not perfect (Eriksen & Eriksen, 1974), the distractor from the right side may disrupt the selection process. By this hypothesis, termed the spatial-attention hypothesis, the interference in the relevant distractor condition is due to competition within the operation of response selection for each hand.

An alternative hypothesis centers on the idea that the interference reflects confusion concerning the mapping between target colors and the two hands. In the relevant-distractors condition, a green object appears on both the left side (the target) and the right side (the distractor). Such an arrangement is susceptible to confusion about the color-hand assignment. By this hypothesis, termed the assignment hypothesis, the added cost in the relevant distractor condition reflects competition between the arbitrary stimulus-response rules.

The present experiment was designed to evaluate these two hypotheses. In all conditions, two target colors, one for each side, were specified for the entire experiment. The color of the distractor was either irrelevant (different from the target for the other side) or relevant (identical to the target color for the other side). We included a manipulation of the horizontal separation between the circles of the two sides (Figure 8). If the spatial-attention hypothesis holds, we would expect to observe a larger cost in the relevant-distractors condition when the distance is small; that is, interference would be greatest when the targets locations on one side are relatively close to the target locations for the other side. The reasoning here is based on previous results showing that the magnitude of the flanker effect is influenced by inter-object distance (Eriksen & Eriksen, 1974).

Please insert Figure 8 here

To test the assignment hypothesis, we included a unimanual condition. Here only two circles were presented on each trial, both on the left or both on the right. The participants were instructed to only move the corresponding hand on these trials. Since they did not know the side of the target in advance, it was necessary to actively maintain both target-color rules. If the distractor color in the relevant-distractors conditions induces rule confusion, we should observe a cost even on unimanual trials. Moreover, the assignment hypothesis predicts that the distance manipulation used in the bimanual conditions should have no effect on the cost of having relevant distractors. This predictions holds because, according to the assignment hypothesis, interference to the selection process of each side is caused by the distractor on that side, activating the competing response rule. Because the distance between the target and distractor on each side was constant, no differences should be observed between the two bimanual conditions.

Method

Participants. Seventeen undergraduate students of the ages 19-26 participated in a one-hour session for course credit or $10 reimbursement.

Procedure. Each trial started with the positioning of the fingers into the starting circles for 1s, a variable foreperiod of 1-2s and the presentation of the target circle(s) and distractor(s). The subjects were instructed to move with the left hand to a circle of one color and with the right hand to a circle of a different color. The designation of target and distractor colors was counterbalanced across subjects. The target colors for each hand remained constant for the entire experiment.

Three conditions (see Figure 8), unimanual, bimanual-near, and bimanual-far, were tested in separate blocks. In the unimanual condition, a single target was presented on either the left or right along with a distractor on the same side. The color of the distractor was either irrelevant (not a target for either hand) or relevant (the color used as the target for the other hand). The bimanual conditions involved movements of both hands, under the presence of either relevant or irrelevant distractors. In the near condition, the horizontal distance between the left and right circles was 10 cm (12°); in the far condition, the distance was 19.5 cm (22°). Distractor types and movement amplitudes were used an equal number of times within each test block in a random order.

The experiment started with three practice blocks of 16 trials each, one for each condition. Following this, 12 test blocks of 32 trials each were conducted. The conditions alternated across blocks and the order was counterbalanced between subjects. After each block the participant received feedback on average response time (RT+MT) and the percentage of correct movements. They were encouraged to go as fast as possible, as long the accuracy did not drop below 85%.

Results and Discussion

The data from two participants were excluded from the analyses. One participant failed to initiate the two movements in a synchronized fashion, having an inter-onset latency difference of greater than 150 ms on over 60% of the trials. The other participant's data were excluded because the effect of distractor type was more than 5 SDs greater than that found for the other participants. For this subject, responses were 130 ms (unimanual condition) and 262 ms (bimanual conditions) faster when the distractors were irrelevant compared to when they were relevant. From the remaining 15 participants, 6.7% of the trials were excluded because the trial was aborted prematurely and 1.6% were excluded because the asynchrony between the hands was more than 150 ms. Of the remaining trials, 4.6% involved an error in which the movement for one of the hands terminated closer to the distractor circle.

The RT data (Figure 9) for the two bimanual conditions revealed a significant effect of the distractor type of 43 ms, $F(1,14) = 1.03$, $p < .001$, replicating the findings of Experiment 2. The distance manipulation did not affect reaction time, $F(1,14) = 1.25$, $p = .28$, and most important, did not interact with distractor type, $F(1,14) = .59$, $p = 455$. Thus, we did not find any support for the spatial-attention hypothesis since this hypothesis predicts that the influence of relevant distractors should have been modulated with spatial distance (Eriksen & Eriksen, 1974). Rather, the results are consistent with the hypothesis that the relevant distractors create interference during response selection due to confusion between the rules regarding the target assigned to each hand.

Please insert Figure 9 here

A reliable 12 ms effect of distractor type was also found in the unimanual condition, $t(14) = 2.79$, $p = .014$. This finding provides additional support for the assignment hypothesis. Although only one target has to be selected in this condition, the presence of a color associated with targets on the other side appears to induce some interference. Note that the distractor effect in the unimanual condition was small and less than half the size of the effect in the bimanual condition. It does not appear that the interference observed in the bimanual condition is simply due to the additive effects found for each hand treated individually.

The movement times (Figure 10) in the bimanual conditions were influenced by the combination of amplitudes, F(3,42) = 85,74, p < .001, as by distractor relevance, F(1,14) = 28.21, p < .001, and these two factors interacted significantly, F(3,42) = 8.12, p < .001. Similar to Experiments 1 and 2, the interaction was due to the fact that the long-long movement combination is especially slowed when the distractors were relevant. In the bimanual conditions, there was a reliable effect of the distance manipulation with MTs slightly longer in the wide condition, F(1,14) = 5.76, p = .031. However, no interaction involving this variable was significant. The effect of distractor relevance was similar for both the near and far conditions, F(1,14) = .5, p = .49.

Please insert Figure 10 here

Within the unimanual condition, the 18 ms effect of distractor relevance was significant, F(1,14) = 13.75, p < .001, and also interacted with movement amplitude, F(1,14) = 6.98, p = .019, again indicating that the long movements were especially slowed down by relevant distractors.

In summary, the results of Experiment 3 fail to support the spatial-attention account of the interference effects observed during bimanual reaching movements under the current conditions. Rather, the results indicate that the interference reflects confusion associated with the assignment of the target colors to the two hands. Interference results when the distractor color is the same as that used for the target for the other hand. This confusion remains constant over distance, and is even present on unimanual trials. Thus, interference does not require competition between a distractor on one side and a target on the other side. Rather, it appears to occur at an abstract level that we assume involves maintaining the stimulus assignments for each hand across trials.

General Discussion

Numerous studies of bimanual coordination have shown that symmetric movements are easier to perform than asymmetric movements (Franz et al., 1996; Franz et al., 1991; Heuer, 1993; Kelso et al., 1983). For example, it is easier to produce movements of the same amplitude than movements of unequal amplitude, what we have referred to as a movement congruency effect. Previous studies have generally emphasized a motor programming explanation of the congruency effect (Spijkers et al., 1997; Spijkers et al., 2000). The assumption has been that it is easier to specify a common movement parameter (i.e., distance) for both hands than to specify different parameters (i.e., two distances), or at a less abstract level, easier to produce similar muscular commands than asymmetric commands. However, these studies have confounded the demands associated with response selection with those associated with motor programming. We sought to dissociate these processing stages. To this end, we developed a task in which target locations were specified on the basis of their color.

Experiment 1 demonstrated that the congruency effect can be reversed when movements of unequal amplitudes are made to targets of the same color compared to movements of equal amplitudes that are directed to targets that differ in color. We also failed to find RT differences between movement combinations that involved the same or different amplitudes in Experiments 2 and 3. These results strongly argue against the motor programming account of the congruency effect. Instead, they are consistent with the idea that the congruency effect arises at earlier processing stages. From this experiment we could not conclude if the effect should be attributed to processes involved in stimulus identification of the cue or response selection.

In Experiment 2, the target colors were specified in advance of each trial, thus reducing the demands on stimulus identification. Nonetheless, the results showed that the cost associated with selecting targets defined by different colors remained. Moreover, we found that the relationship between the colors used for the targets and distractors on opposite sides, what we refer to as distractor relevance, had a dramatic effect on RT. RTs were much slower when the distractor color for one hand was the same as the target color for the other hand. We conclude that while the costs associated with stimulus identification may have contributed to the results of Experiment 1, the main source of interference in the preparation of bimanual movements is associated with selecting the targets of the reaches.

We examined the selection costs in further detail in Experiment 3, comparing two hypotheses that could account for the distractor relevance effect. By the spatial-attention hypothesis, the presence of a distractor object of the target color requires a filtering process that can be by-passed when the distractor is of a different color. For example, if the right hand is to move to the green circle on the right, spatial attention is required to eliminate interference from a green distractor on the left. As an alternative, we proposed the assignment hypothesis. By this account, the inclusion of distractors in the target color of the other hand activates a competing response rule. This increases the demands on processes involved in maintaining the assignment of target colors to the two hands. The magnitude of the distractor relevance effect was unaffected by an increase in the distance between the locations of the two sides. In addition, this effect was also present even on unimanual trials. Thus, the results favor the assignment hypothesis.

How are movements selected?

Our results appear to be at odds with previous studies that have emphasized the importance of motor programming (Spijkers et al., 1997; Spijkers et al., 2000). We believe our response selection account can also apply to these studies, but that it is also important to recognize that the manner in which movements are selected and represented depends on the task requirements. In the experiments of Spijkers et al., the symbolic cues specified the target amplitude. For example, the German words for “short” or “long” or a short or a long bar indicated if the amplitude of the movement should be short or long. It is likely that these movements were represented in a similar manner, e.g., as a “long” or “short” movement. In the present experiments, the selection is based on the color of the object; for example, the goal is to move to the red or green circle. We propose that this influences how the possible movements are represented. When the targets are selected as a red or green circle, there appears to be no explicit representation of the required amplitude, an account of why we observe no difference between conditions in which the movements are of the same or different amplitudes.

By this view, the congruency effect is based on the manner in which the actions are represented. Indeed, in our previous work (Diedrichsen et al., in press), we observed no interference when the two targets were presented without any distractors. Under such conditions, the movements are selected in terms of a target location and there is no need for intermediate, more symbolic representations. The target locations themselves specify the necessary movement parameters. In contrast, many psychological studies require key presses which are arbitrarily assigned to stimuli as responses. Under these conditions, we would expect that the responses are selected based on the relative position of the key. For example, when each hand has to make an upper or lower key press, interference between the two actions is based on the location of the key (Hommel, 1998; Lien & Proctor, 2000).

Our emphasis on how actions are represented is related to the common coding theory developed by Hommel and his colleagues (1993). The theory is inspired by a number of elegant demonstrations showing how the consequences of an action will influence the representation of the action. One set of experiments involved a variant of the Simon task (Simon & Small, 1969), a two-choice reaction time task in which participants identified a (non-spatial) visual stimulus. The stimulus could appear on either the left or right side of the display and the participants responded on keys oriented along the same axis. The critical modification was that pressing the keys caused one of two lights to become illuminated. The mapping between the key presses and action-triggered lights was varied such that in the uncrossed condition, a key press illuminated the light on the same side and in the crossed condition, the key press illuminated the light on the opposite side. The uncrossed condition produced the standard Simon effect: responses were faster when the stimulus was in spatial correspondence with the response key. However, the effect was reversed in the crossed condition; responses were faster when the stimulus appeared on the opposite side. Thus, the (irrelevant) spatial code generated by the position of the stimulus did not interfere with the spatial code associated with the response itself, but rather with the spatial code associated with the consequences of the response. In accord with this theoretical position, we believe that the patterns of interference in bimanual studies are also not based on the specifics of the movements themselves, but rather in terms of how the actions are represented.

Focusing on how a movement is represented and selected can also shed light on the debate concerning the validity of the movement precueing task (Rosenbaum, 1980; Rosenbaum & Kornblum, 1982). Reaching tasks have been widely used to test the processes involved in the specification of movement parameters. For example, in an experiment by Rosenbaum (1980), participants made one of eight movements following the presentation of a colored circle. Each color represented a unique combination of three binary dimensions, hand (left or right), direction (forward or backward), and amplitude (short or long). On some trials, letters precues were presented to specify in advance the hand, direction, and/or extent of the movement for the forthcoming trial. From the pattern of benefits observed across the various cueing conditions, it was concluded that while the sequence of parameter specification was flexible, information about the hand was more beneficial than specification of movement direction, which in turn was more beneficial than specification of amplitude.

The characterization of these benefits in terms of advance specification of motor parameters has been questioned. Goodman and Kelso (1980) used the same precueing logic. However, instead of using letters relating to movement parameters as precues, they illuminated the possible target positions. Thus, if the precue were to indicate that the trial would involve a right hand movement, all four possible target positions on the right would be illuminated. In a similar manner, the target location was directly indicated by the illumination of that single location. With these direct cues, the differences between the types of precues were eliminated. The benefits of cueing were now based solely on the number of S-R alternatives. This was also true if the precued target locations differed on all three movement parameters, so that no preprogramming could be done (see also Reeve & Proctor, 1984, 1985).

The difference between the symbolic and natural cues in the precueing task provides further evidence that response selection is strongly influenced by the underlying representational codes. With the symbolic cues, the participants learn for example to characterize the response to a green circle as a “long, forward movement with the left hand”. If the response selection works on these codes, a precue indicating one of the movement parameters would ease the selection process. In contrast, with the direct cues, the movements are coded as potential locations for the response. Under this condition, precues indicating particular movement parameters are no longer helpful since these parameters are not part of the representation and cannot be used to guide selection (Goodman & Kelso, 1980; Reeve & Proctor, 1984). Similarly, the interference connected to the execution of two movements of different amplitudes disappears

The locus of bimanual interference

The proposal that target selection provides a limiting constraint to the performance of bimanual movements suggests an intriguing link between the present results and those obtained from dual-task experiments. Perhaps most relevant are studies proposing that dual-task performance is constrained by a structural bottleneck in the cognitive architecture that performs response selection and necessarily operates on a single task at a time (Pashler, 1998b). According to such accounts, the principal source of interference between temporally-overlapping tasks is competition for this response-selection bottleneck. If one assumes that the same-target conditions require the response-selection bottleneck only once whereas the different-target conditions require the operation of the bottleneck twice, then this account provides a succinct explanation for the costs between to the types of conditions.

However, a response-selection bottleneck on its own is insufficient to account for the finding that relevant distractors produce greater dual-task costs than irrelevant distractors. While this result is not evidence against the existence of a response-selection bottleneck, it does suggest that the selection process for one hand interact with those for the other hand. One account for the costs associated with relevant distractors supposes that there exists an uncertainty when different rules are assigned to the two hands. That is, selection processes can be influenced and slowed by other activated codes, as for example a competing response rule held in working memory. The uncertainty has to be resolved before the response is made, leading to prolonged reaction times. The presence of distractors that match the target color of the other hand activates the other response rule and increases the uncertainty.

Along with explaining the RT difference between the different-targets, irrelevant-distractors and different-targets relevant-distractors conditions in Experiment 2, the assignment hypothesis provides a parsimonious account of the findings in Experiment 3.

Even in the absence of a second task, a distractor stimulus that activates the task-rule for the other hand can induce a substantial cost. People have great difficulty in maintaining conflicting agendas for the two hands. Fortunately, such situations rarely arise in normal environments.

This assignment hypothesis is closely related to the concept of feature binding in the motor domain. Hommel and colleagues (2001) propose that all relevant features of the actions must be bound into an action plan before a volitional movement is executed. This binding process is analogous to the feature binding process proposed in theories of visual perception required when target stimuli cannot be identified by the presence of a unique visual feature (e.g., Treisman & Gelade, 1980). For example, in our experiment the code representing a yellow target would be bound with the code for the left hand and the code representing the red target has to be bound to the code for the right hand. The presence of a red distractor on the left side would make binding of the relevant features more difficult, because the red distractor code is highly activated due to its relevance for the other side. In the same-target condition the assignment problem vanishes, either because the shared color can be bound to a single action plan for both hands or because binding may not be necessary at all.

Other sites of interference and cross talk in bimanual performance

The current studies have focused on interference effects that arise during response or target selection and are apparent in the initiation times of the movements. There is abundant evidence that interactions of different movement parameters also emerge during planning and execution of bimanual. Much of this interaction occurs in the temporal domain. For example, actions of the two hands tend to synchronize with each other (Kelso et al., 1979; Kelso et al., 1983), even when the movements are directly cued (Diedrichsen et al., in press). However, interactions are also seen in the spatial domain. When the trajectory for one hand has to be modified due to the presence of an obstacle, the trajectory for the other hand is also altered (Kelso et al., 1983). Similarly, spatial assimilation effects are seen when people are asked to draw two different shapes such as circles with one hand and lines with the other (Franz, 1997; Franz et al., 1991) or produce fast reversal movements of different amplitudes (Heuer, Spijkers, Kleinsorge, van der

Loo, & Steglich, 1998; Marteniuk et al., 1984; Sherwood, 1994). Heuer and colleagues (Heuer, 1993; Heuer, Kleinsorge, Spijkers, & Steglich, 2001) have also distinguished between spatial cross talk arising during motor programming and motor execution stages by varying the time available to plan the movements. In summary, there is considerable evidence that there exist multiple kinds of movement coupling on other stages than response selection.

At present, we hypothesize that the interference observed in the reaction time is primarily determined by how the movements are conceptualized. It remains to be seen if a similar mechanism can account for interference observed as coupling of kinematic parameters during movement execution, or whether interference here is based on the relationship between the movements themselves as has been emphasized in the literature. One finding that supports the first view is that spatial interference between movements can be greatly reduced, if the two movements can be conceptualized as a common goal or purpose (Franz, Zelaznik, Swinnen, & Walter, 2001). Nonetheless, we believe there is accumulating evidence that interference arising at response-selection on the one side and movement planning or execution on the other side, can be dissociated.

We have observed in our studies with callosotomy patients dramatic examples of the dissociation of these sources of interference. In one recent study using a bimanual isometric force production task (Diedrichsen, Hazeltine, Nurss, & Ivry, in preparation), the callosotomy patients exhibited pronounced coupling: the two hands generated similar forces even when the target forces for the two hands were different. Indeed, the extent of coupling was similar to that found in neurologically healthy controls. However, the patients did not show any cost in terms of the time required to initiate the responses. Their RTs were similar for same-force and different-force trials. Controls, on the other hand, were much faster initiating same-force trials. Thus, the callosotomy patients exhibit a decoupling within the response selection process, yet normal parametric coupling in terms of the execution of the responses.

Conclusion

Interference during the performance of bimanual actions may occur at different processing stages. In the context of our example from the introduction, there may be many causes for the limitations on our ability to bimanually pick out good cherries among rotten ones simultaneously with two hands. We explored three possible constraints on performance: (1) limits in selecting one target object at a time, (2) interference when different movement parameters have to be specified for the two hands, and (3) cross talk in the trajectory between hands when movements of different length or direction have to be executed. The results from three experiments consistently favored the first explanation, constraints in target selection. This process may become especially demanding, if different rules govern each hand and if distracting information creates ambiguity as to which rule should be applied.

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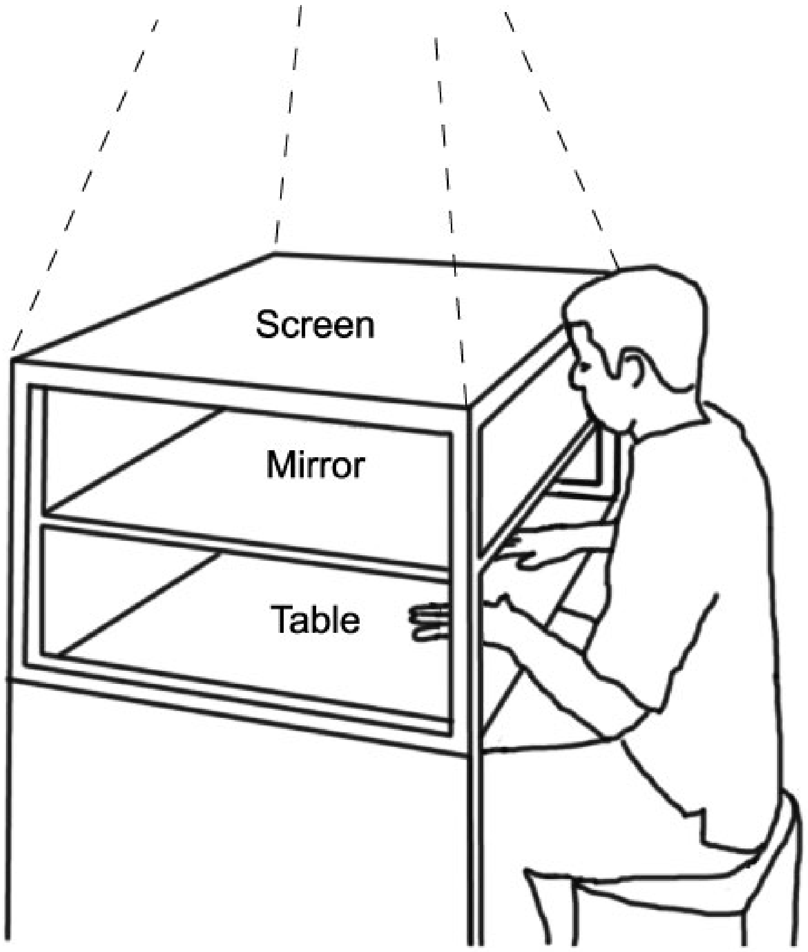
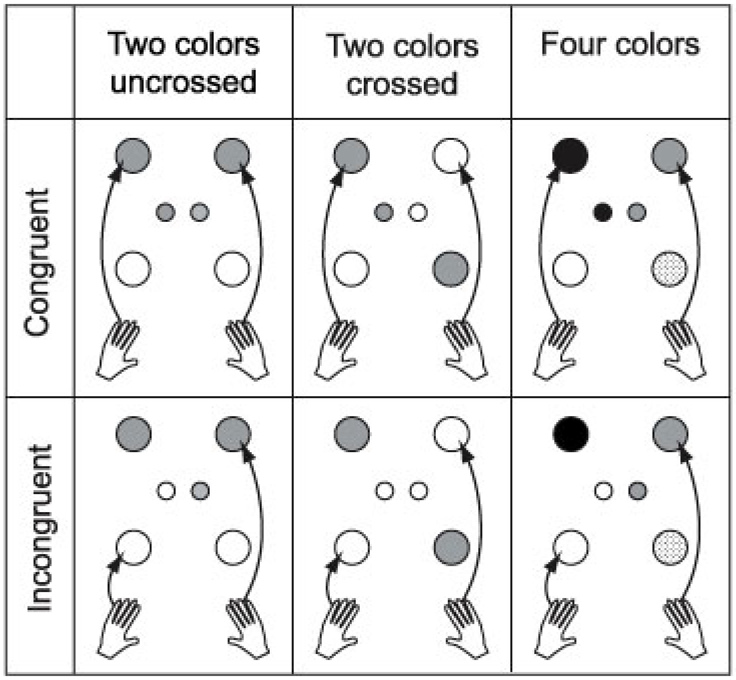
Figure Captions



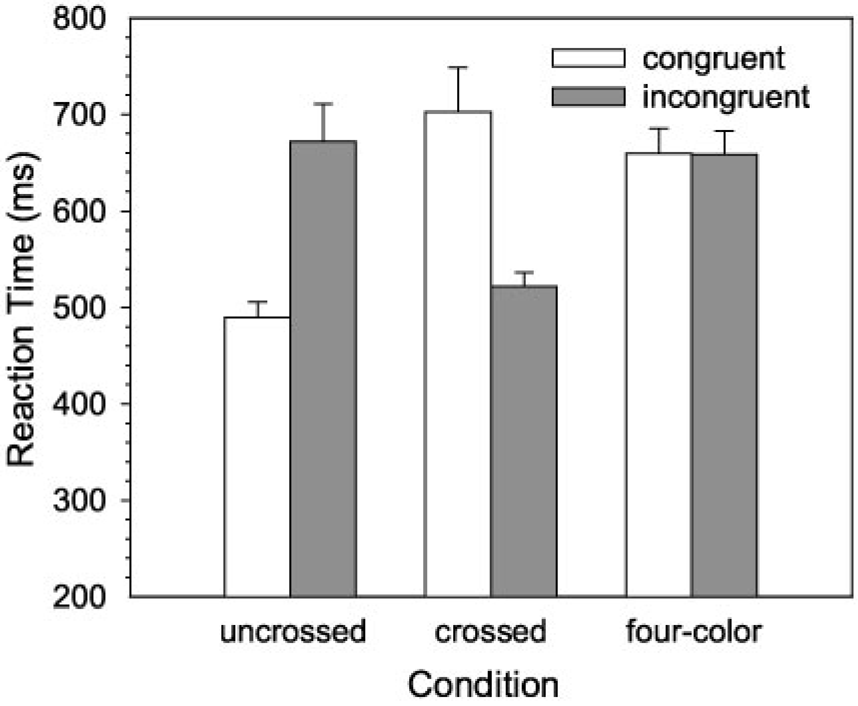
Diedrichsen et al., Figure 1

Figure 1. Apparatus used in all three experiments. The participant is seated in front a table surface and looks onto a mirror, the head stabilized with a chin rest (not shown). A computer projector displays visual stimuli from above onto the screen (dashed lines). Because the participant views the screen through the mirror, which is equidistant between screen and table, the impression arises that the stimuli reside on the table surface. The participant can not see its hands directly, however, the position of the tip of both index fingers is tracked with a movement recording system and a small dot is presented at the corresponding locations on the screen.



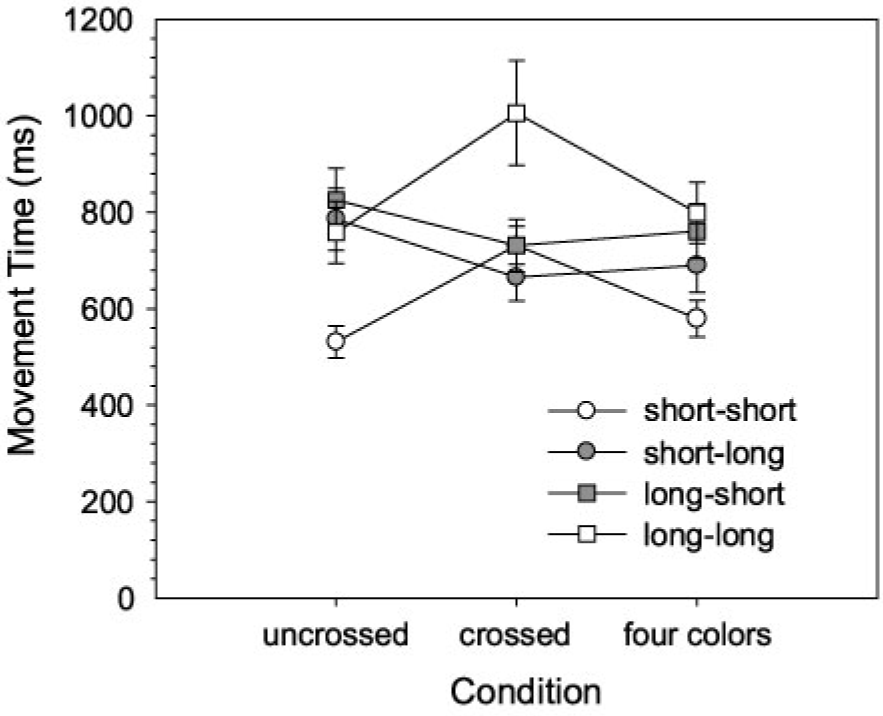
Diedrichsen et al., Figure 2

<u>Figure 2.</u> Experimental conditions for Experiment 1. Four colored circles arranged in a square were presented, indicating the possible target locations. After a delay interval, two smaller colored circles appeared in the center and served as the cues. Participants were instructed to reach with each hand to the target location that matched in color the cue on that side of the display. The amplitudes of the two movements could either be identical (congruent, top row) or different (incongruent, bottom row). Three conditions were tested. Left column: The target colors for the two sides were in spatial correspondence in the uncrossed condition. Middle column: The target colors for the two sides were spatially crossed in the crossed condition. Right column: The two targets and two distractors were all different colors in the four-color condition. The actual colors were green, red, blue and yellow, here represented through shading and pattern.



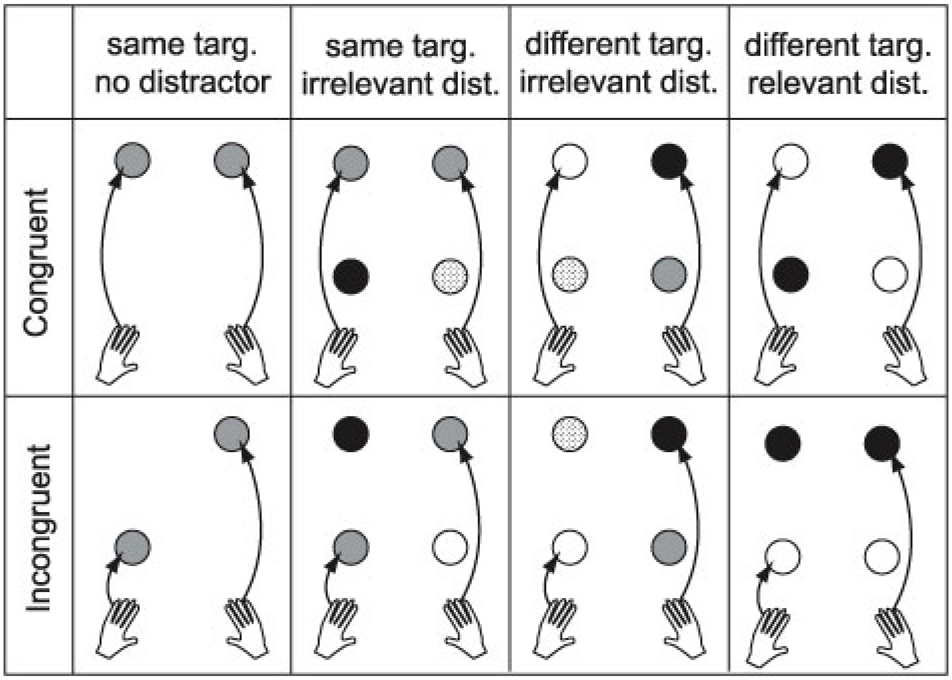
Diedrichsen et al., Figure 3

Figure 3. Reaction times for Experiment 1. Results are shown for the three conditions as a function of whether the two movements were congruent or incongruent in terms of their amplitude. Error bars indicate between-participant standard errors.



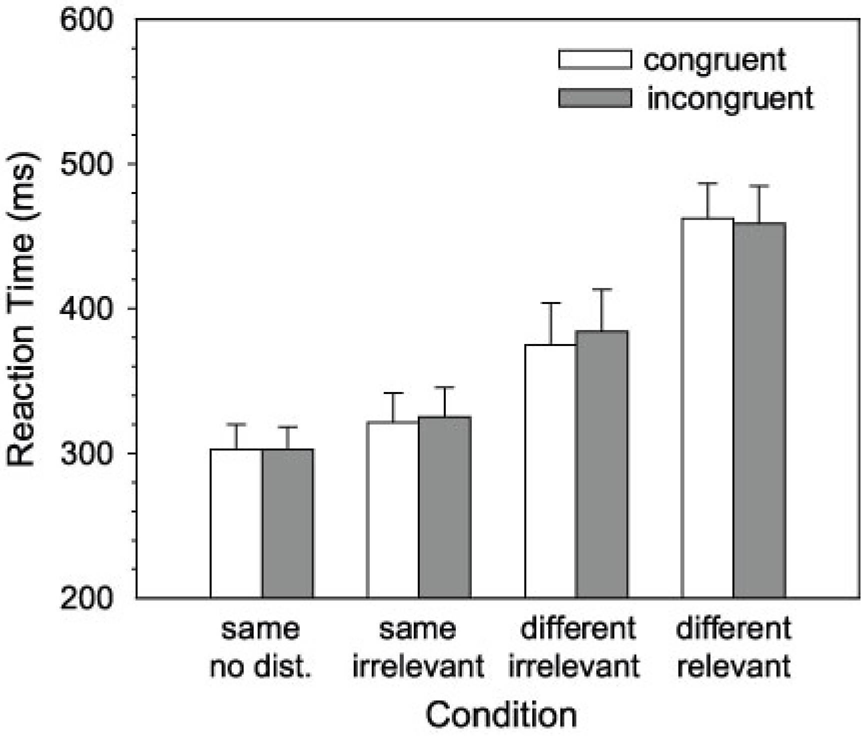
Diedrichsen et al., Figure 4

Figure 4. Movement times for Experiment 1. Results are averaged across the left and right hand. The data are plotted in terms of the MT for a movement of given amplitude (indicated by the first amplitude listed in the legend) as a function of the amplitude required of the other hand (indicated by the second amplitude listed in the legend). Error bars indicate between-participant standard errors.



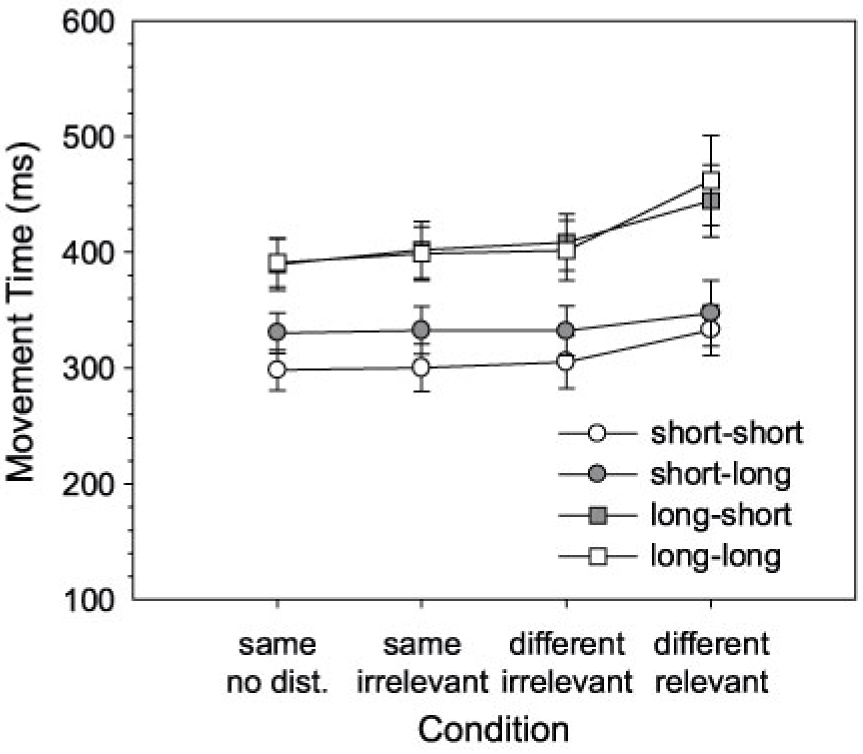
Diedrichsen et al., Figure 5

Figure 5. Experimental conditions in Experiment 2. In the same-target conditions subjects were instructed to move with both hand to targets of one color (here gray). In the different-targets conditions the movement of the left had to be directed to a target of a different color than on the movement of the right hand (here white on the left side, black on the right). In the same-target, no-distractor condition (first column) only the two target circles were present. Irrelevant distractors were present in the same-target, irrelevant-distractor condition (second column) and the different-targets, irrelevant-distractor condition. Irrelevant distractors were circles in colors, which were different from the selected target-colors. In the different-targets, relevant-distractors condition (last column), the color of the distractor on one side matched the color of the target on the other side. The movement could either have identical amplitudes (congruent, upper row) or differ in terms of their amplitude (incongruent, lower row). The actual colors were red, green, blue, yellow and gray, here represented through shades.



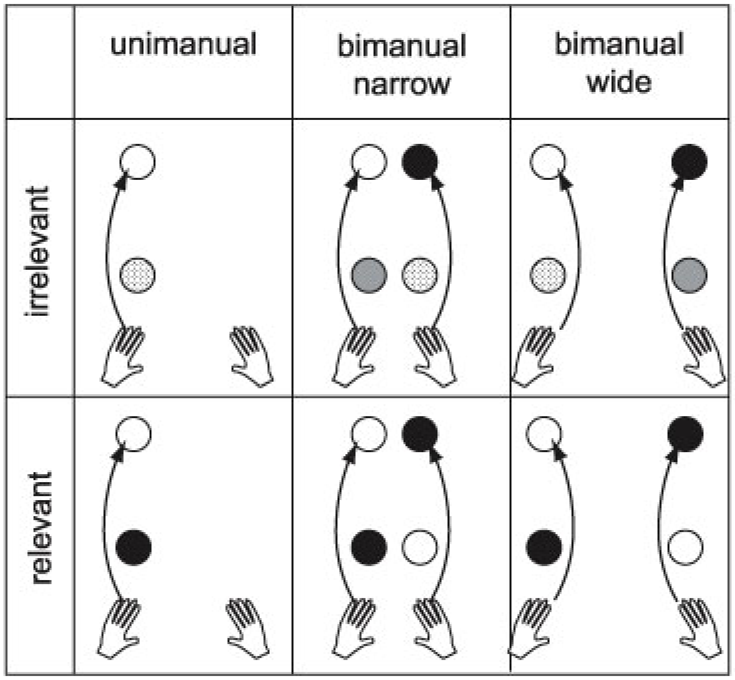
Diedrichsen et al., Figure 6

Figure 6. Reaction time for Experiment 2 plotted as a function of the experimental condition and movement congruency (same or different amplitude).



Diedrichsen et al., Figure 7

Figure 7. Movement times for Experiment 2 in the same-target and different-target conditions. Identical conventions as in Figure 4.



Diedrichsen et al., Figure 8

Figure 8. Experimental conditions in Experiment 3. Throughout the whole experiment, movements to circles of different colors had to be made with the left and right hands (here white on the left, black on the right). The target colors for each hand remained constant for the entire session and the distractor colors were either irrelevant (never targets) or relevant (target for the other hand). In the unimanual condition, a target and distractor appeared on only one side, selected at random. In the bimanual conditions, the targets and distractors o the two sides could be separated by a wide or narrow gap. As in the last experiment movement amplitudes could be either congruent or incongruent (not shown).

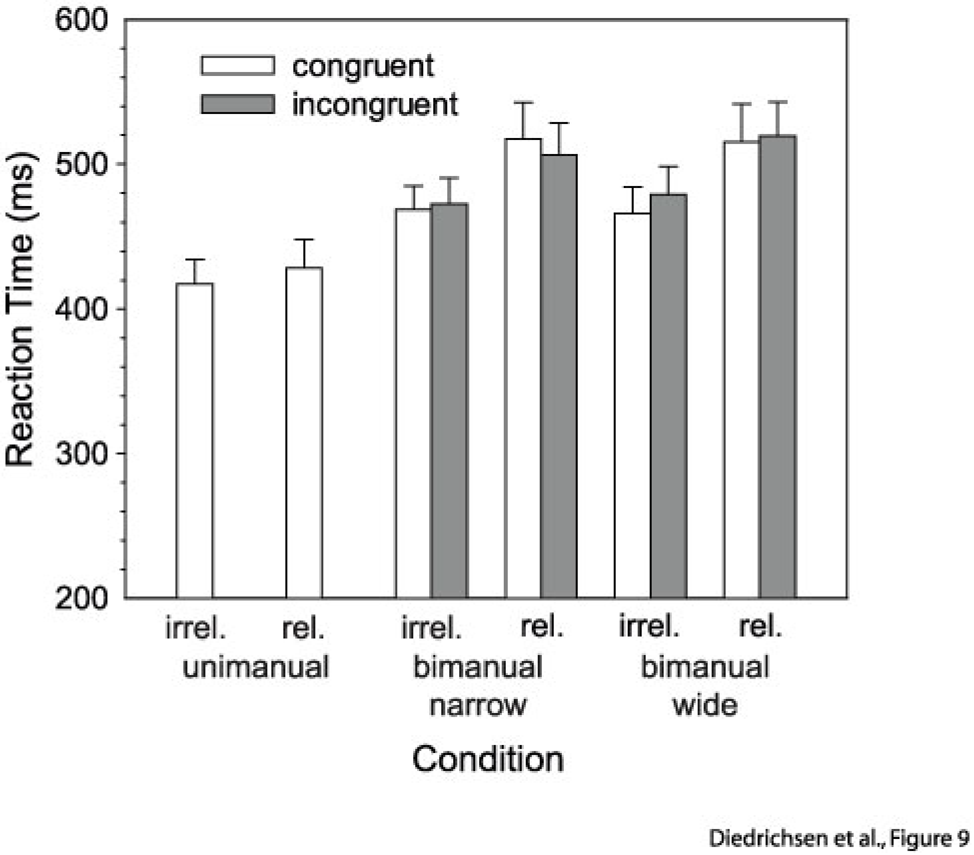


Figure 9. Reaction times for Experiment 3 plotted as a function of condition and movement congruency (same or different amplitude). Note that congruency is not applicable in the unimanual condition.

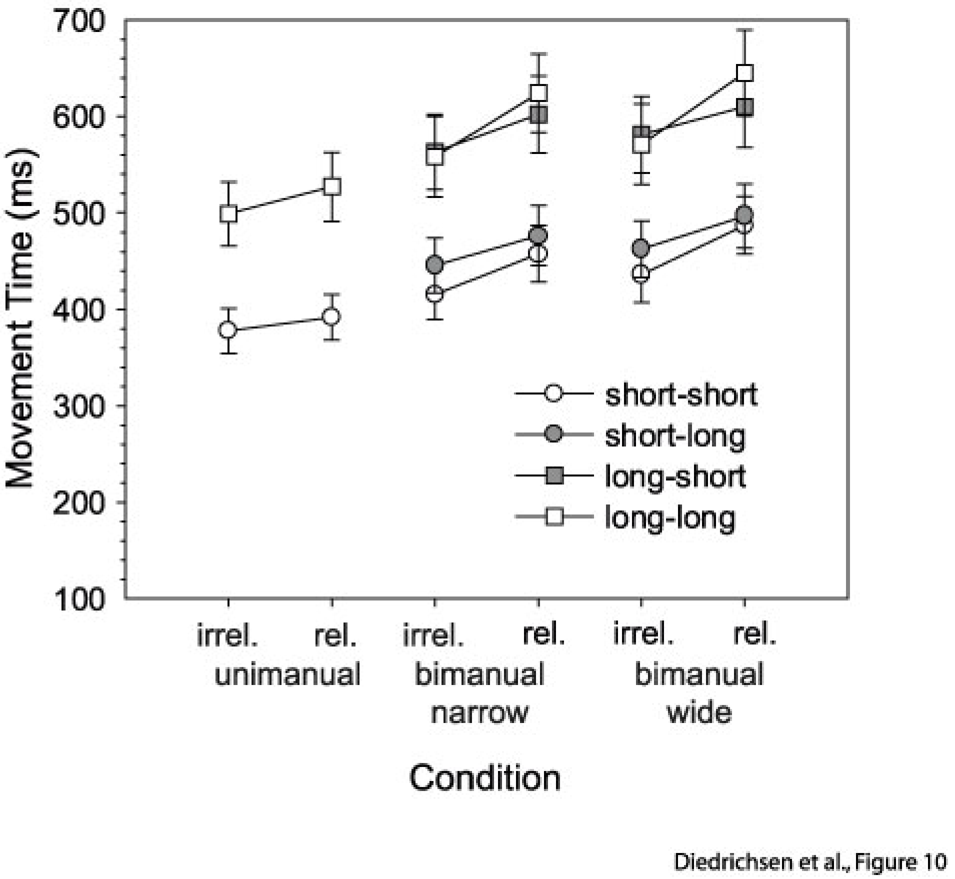


Figure 10. Movement times for Experiment 3 in the unimanual condition and the two bimanual conditions. Identical conventions as in Figure 4.